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THE ROLE OF ATTENTION IN INFORMATION PROCESSING

IMPLICATIONS FOR THE DESIGN OF DISPLAYS

Lynn C. Oatman

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A principal goal in human factors engineering (HFE) is to develop a theoretical an empirical basis for matching the attentional mechanisms of the human operator with th appropriate information portrayed by the visual display. Since a display serves as a interface between the human operator and a dynamic system, its structure and composition ar critical to the operator's performance. A display compatible with the human operator' attention mechanisms will improve performance by allowing faster, more accurate informatio processing, and will minimize mental work load.

The system designer has to predict which attention mechanism an operator will use in specific task situation. A very effective human-system interface will result if th designer succeeds in matching the displayed information with the appropriate attentio mechanism. If the designer has no information about the human operator, however, or a mis

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conceived model of attention mechanisms, the operator's performance may be worse, and designers will continue to be frustrated in their attempt to minimize potential errors.

This report reviewed several different classes of attention models, such as filter models, resource models, and spatial models, which are descriptions of the functioning of the human operator's attention mechanisms to extract information from visual displays during the performance of different visual tasks. Research conducted at the U.S. Army Human Engineering Laboratory (HEL) has been reviewed and related to the appropriate attention models to construct a better concept of the functioning of the attention mechanisms. Finally, the models are discussed in terms of the practical implications for the design of displays.

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JOHN D. WEISZ
Director
Human Engineering Laboratory

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INTRODUCTION

One of the major areas of human factors research has been in the design of displays for military aircraft, field artillery systems, and military electronic systems. A display serves as an interface between the human operator and a dynamic system, and its structure and composition are critical to the operator's performance. As the complexity of systems has increased, the amount of information available to the human operator has become overwhelming. Technology has given the system designer a wealth of novel display concepts (color, three-dimensional displays, voice input, and high speed graphics). As Wiener and Curry (1980) have noted, the major issue in cockpit design is no longer whether certain flight deck functions can be presented but whether they should be. Therefore, there is a serious need in basic human engineering to determine what functions should be presented and to optimize the display formats used to present system information.

The two major areas of research directed at design criteria for displays have dealt with (a) the information itself and (b) techniques for formatting, coding, or organizing the displayed information. However, neither of these areas of research has adequately considered the capabilities and limitations of the human operator as a design element in human-system interfaces. One purpose of this report is to examine the capabilities and limitations of the human operator's attention mechanisms in the processing of information from displays. A second purpose is to demonstrate how knowledge of these attention mechanisms can be an important consideration in the formatting, coding, and organization of displayed information.

A principal goal in human factors engineering (HFE) is to design a visual display format that will match the attentional mechanisms of the human operator. Attention mechanisms have been difficult to define but have been conceptualized as mechanisms that direct the processing of information, that is, allow the human operator to select one source of information instead of others, focus on one class of events while ignoring others, and do more than one task at the same time. A display compatible with the human operator's attention mechanisms will improve performance by allowing faster, more accurate information processing and will minimize mental work load. To accomplish this goal, the system designer must develop not only a conceptual model of the system that is appropriate for the user, that captures the important parts of the operation of the system, and is understandable by the user (Norman, 1988), but also must develop a conceptual model of the functioning of the attention mechanism to extract information from the display interface. The designer has to predict which attention mechanism an operator will choose in a particular task situation. If the designer succeeds in this prediction, a very effective human-system interface may result; if not, operator performance may be worse (Rasmussen, 1986). Thus, attempts to improve system design from misconceived models about the human operator will continue to frustrate designers in their attempt to minimize potential errors (Jahns, 1987).

Although there is a staggering volume of seemingly relevant human performance data and behavioral principles in the research literature, these data are not adequately factored in the design of human-system interfaces. Why is it that basic research findings that appear to have significant implications often are not used by human factors specialists and designers? In general, issues regarding the use of findings from basic research are complicated, and there are many potential impediments to the implementation of research findings to design decision making. A number of factors contribute to the problem, including the practical usefulness of the data (Rouse, 1985), the accessibility and interpretability of the human factors research literature (Boff, 1988; Boff & Lincoln, 1988), and conditions that shape the perceived value of research findings (Boff, 1988).

The transition of basic research findings to design applications has fostered an active controversy in human factors literature. On the one hand, Meister (1984) has stated that basic research has been of little value to human factors practitioners. Basic researchers have too frequently selected tasks so far removed from reality that their results are not analogous to any real-world circumstances (Simon, 1987). As a result, experiments on vision and visual displays have generally failed to provide the data needed to quantitatively predict performance under operational conditions. The designer's effectiveness in applying human factors principles "continues to depend upon his own experience and intuition" (Meister, 1984; Kantowitz, 1985).

On the other hand, Smith (1987) has observed that human factors studies are performed year after year to answer the same questions, yet those questions remain unanswered. Experiments have been too narrow and lack generality, and when problems arise, a new experiment must be conducted because the data from previous experiments are not applicable. If the data were more generalizable (Smith, 1987) and were collected more effectively (Simon, 1987), human factors specialists would be prepared to provide answers to designers' questions.

Given the infinite modifications and combinations of relevant factors in real-world situations, there will never be a handbook with enough data to cover all problems that must be solved (Boff, 1988). However, Rouse (1987) has argued that data are seldom the issue or an end in themselves, but the real issue in system design is concerned with understanding the problem in order to formulate one or more solution concepts. Although data are important as a means to test hypotheses about human abilities, limitations, and preferences, and thus determine our understanding of behavioral phenomena, Rouse (1987) argues that designers "must go beyond the data!" This suggests a form of informal theorizing bound by the designer's experience, intuitions, and common sense in which designers must be willing to interpret results in terms of practical implications and then extrapolate to design decisions that would otherwise be completely ad hoc.

Kantowitz (1985) asserts that the use of theory enables us to go beyond the data. Theories offer generality, which can be applied to many different practical problems, thus allowing designers to recognize similarities among problems. A theory fills in when data are lacking and can yield the precise predictions that can aid in the solution of practical problems. A theory can also assist the designer with the formulation of a conceptual model about human abilities, limitations, and preferences.

Since the designer's effectiveness in applying human factors principles continues to depend largely on his or her own experience and intuition (Meister, 1984; Kantowitz, 1985), it is important to provide system designers with better theories and models of human attention mechanisms. These goals can be achieved from the basic research conducted at the U.S. Army Human Engineering Laboratory (HEL) on attention mechanisms related to the processing of auditory-visual information from displays. The research program has focused on the attention mechanisms of the human operator per se--how do attention mechanisms function to extract and process information? To answer this question, we must know how the human operator's sensory systems extract information, how that information is processed in the brain, and how the operator responds as a result of that processing. We also need to know the extent to which the working environment degrades the operator's performance. When we have this information, system designers will be able to improve the human-system interface by designing displays that are compatible with the human operator's attention capabilities and limitations.

This report first reviews a general framework or concept of attention. Next, the models and theories of selective attention mechanisms are briefly reviewed. The review is not intended to include all the models of attention, but the models discussed in this section show how the attention mechanism is thought to function in extracting and processing information from displays. Research conducted at HEL is reviewed and related to appropriate models to construct a better picture of the functioning of the attention mechanisms. Finally, the implications of a model are discussed in consideration of the formatting, coding, and organization of displayed information.

CONCEPT OF ATTENTION

One of the most important concepts in the field of human performance is attention. Attention has been difficult to define, but has been viewed as an important component of human information processing. Attention is conceptualized here as a control mechanism that functions to direct the processing of information toward specific objectives.

Everyday experience suggests that attention can somehow be directed to objects or tasks. Three types of tasks involving the direction of attention are often encountered in human-machine interactions: selective attention, focused attention, and divided attention. In one type of task, the human operator is required to monitor several sources of information to determine whether a particular event has occurred. The selection of one event instead of others constitutes selective attention, such as a pilot scanning the instruments, looking for a deviant reading.

In some cases, the human operator may be instructed to attend to one source of information and exclude other sources. This is called focused attention, in which, for example, a radar operator may be instructed to attend only to blips in a certain sector of his or her screen and to ignore others, or the pilot who attends to selected visual targets and ignores others.

In another situation, called divided attention, two or more separate tasks must be performed simultaneously, and attention must be paid to both. Whereas the human operator can easily selectively attend to one object or task, it is more difficult to attend to two or three objects or tasks at the same time. It is important to determine the number and kinds of objects or tasks an operator can attend to at the same time. Selective, focused, and divided attention are discussed in more detail, and some of the human capabilities and limitations associated with them are indicated.

Selective Attention

Selective attention refers to a mechanism that allows a human operator to select one object or source of information instead of others. The main function of the attention mechanism is selection of relevant sources of information at the expense of irrelevant information to ensure adequate processing of the currently important sensory messages (Kahneman & Treisman, 1984).

A prominent feature of the attentional mechanism is that it is limited in the number of operations it can perform at a given instant in time. Selective attention presupposes that there is some capacity limitation or bottleneck in the processing system and that operators have the ability to give preference to some information so that it passes through this bottleneck easily and at the expense of other information. The discovery of surprising limitations in the handling of simultaneous messages by air traffic controllers indicated that the capacity of the human organism is limited. The human operator will become overwhelmed unless it selects from the multitude of information the one message that it wants to accurately process.

In many situations, complex displays of information are presented over several channels simultaneously. The information might be within the same sensory modality or it might be between two sensory modalities. For the designer to understand performance in complex tasks, it is necessary to know to what extent human operators are capable of selecting information. Sanders and McCormick (1987) indicated that when operators have to sample multiple channels of information, they tend to sample channels in which signals occur very frequently rather than those in which the signals occur infrequently. In addition, operators often forget to sample a source when many sources are present, and operators tend to sample sources more often than would be necessary because they cannot remember the status of the source when it was last sampled (Moray, 1981). Under conditions of high stress, fewer sources are sampled, and the sources that are sampled tend to be those perceived as being the most important and salient (Wickens, 1984).

Focused Attention

Focused attention refers to the human operator's ability to focus on one class of important events and to ignore extraneous events. Many of the tasks performed by pilots during flight demand an ability to focus attention on relevant aspects of displays while ignoring irrelevant aspects of displays, to switch rapidly from one display to another, and to avoid interference from distracting displays of information. With the change in the role of pilots from

manual flying to monitors of automated flying systems (Kessel & Wickens, 1982; Gopher, 1982), it is necessary for designers to know to what extent human beings are capable of focusing attention.

The evidence seems to indicate that human beings can selectively focus attention on whatever aspect of the arriving information that is of interest; information arriving via a specific sensory modality, for example, via the right ear (Broadbent, 1958; Cherry, 1954; Treisman, 1960, 1964); its specific spatial location, for example, attending to locations with the control of eye movements and independently of fixation (Posner, 1980; Posner, Snyder & Davidson, 1980); a temporal sequence of information (Hamilton & Hockey, 1974); specific sensory features, for example, to a specific shape, color, or size, (Egeth, 1977; Francolini & Egeth, 1980; Treisman & Gelade, 1980; Treisman, 1982); common sensory qualities, for example, to letters or digits (Egeth, Jonides, & Wall, 1972; Shiffrin & Schneider, 1977); or to words belonging to a prespecified category (Fisk & Schneider, 1983).

Sanders and McCormick (1987) have indicated that the problem with focused attention is to maintain attention on one or a few sources of information and not be distracted by other sources of information. The ability of the human operator to maintain focus of attention is influenced by the closeness of the sources of information in physical space. If two visual sources of information are within 1^{o} of visual angle from each other, it is nearly impossible to maintain focus of attention on one source of information and completely ignore another (Broadbent, 1982). When more than one source of information occurs at the same time, but only one must be attended to, performance can be improved if the sources of information are made distinct from one another, that is, make the source of information of interest larger, brighter, louder, or more centrally located than the competing sources of information (Sanders & McCormick, 1987).

Divided Attention

Divided attention refers to the human operator's ability to do more than one task at the same time. This type of situation is also referred to as time-sharing (Sanders & McCormick, 1987). Humans can try to divide their attention between two conversations instead of selectively attending to just one of them, but they find such eavesdropping very difficult. Early studies of attention typically involved complex competing messages, often speech, which constituted a high perceptual load. Humans appeared to do quite poorly in dividing attention between such messages, but they were very successful in focusing attention at will on one of them (Kahneman & Treisman, 1984).

Divided attention tasks are used to establish limits of performance and to measure the extent to which different tasks can be combined without loss. It is generally agreed that humans have a limited capacity to process information. When human operators are required to perform several tasks simultaneously, that capacity can be exceeded, and performance of at least one of the tasks often declines (Sanders & McCormick, 1987). Researchers have been interested in determining how many tasks can be done at one time and predicting which tasks can be performed simultaneously, and then generating models that reflect the structures underlying the attention mechanisms. However, the answers to such questions depend on the experience of the human operator, the nature of the

tasks, and the relation between the tasks (Hirst, 1986). Divided attention tasks are also used to analyze the causes of dual task decrements and to determine the stages of processing that limit performance.

MODELS OF ATTENTION

Models of the human information-processing system were primarily designed to account for the human operator's attention to certain stimuli while ignoring others (i.e., selective attention) and the degree to which the operator can process several things at once (i.e., divided attention).

One class of models proposes that perceptual analysis of the visual display takes place in two successive stages. Stage 1 requires a parallel mechanism (preattentive) which rapidly and readily extracts features such as color or movement within the entire visual display. Simultaneous processing performed in parallel without interference is characterized as fast, inflexible, and "attention-free" and often said to be automatic (Hoffman, Nelson, & Houck, 1983).

Such a processing mechanism in human visual performance is clearly illustrated when the human operator tries to detect the presence of a particular target among different objects. When the target differs from other objects in the display by a single feature, such as color or orientation, it can be found easily and appears to pop out from the background (Hoffman, 1986). The processing leading to its detection is rapid and relatively independent of the total number of objects in the display.

Stage 2, a limited capacity mechanism, requires detailed analysis of the content of limited areas of the visual display (focused attention). Focused attention is serial and thus is characterized as slow, flexible, and demanding of attention in the sense that external elements compete for a common limited capacity resource (Posner & Presti, 1987). Thus, when two (or more) such attributes are needed to distinguish the target, the processing is difficult and the time required for its detection increases linearly with the number of elements in the display (Treisman & Gelade, 1980). Only in this second stage is there a limit on the ability of the operator to handle several stimuli at once.

The two-stage models fall into the class of bottleneck or filter models. This class of attention models proposes a limited capacity mechanism or filter that blocks or attenuates all incoming messages that differ from the attended messages and allows only the selected message to be further processed. The filter mechanism selects attended messages based on the stimulus features of the competing messages. According to these models, messages that do not share the same stimulus features as the attended message should not get through the filter.

These models suggest that the primary bottleneck in processing simultaneous inputs is in Stage 2 where focused attention is serial and processes only one input or task at a time. However, the models differ in location of the alleged bottleneck, at an "early" or "late" stage of process.

Another class of models proposes that various attention mechanisms draw on limited resources. Some resource models have suggested that a single resource pool is used for all attention mechanisms (Kahneman, 1973); others have argued

for multiple resources used in different attention mechanisms (e.g., Wickens, 1980). The central idea is that the various attention mechanisms may be scheduled to function concurrently; however, the speed and accuracy of their operation will be limited by the quantity of resources they are allocated. In this context, attention may be modeled as a commodity or resource of limited availability. If some processes require more of this resource, less is available for other processes whose performance will therefore deteriorate. For example, a driver may stop talking in a car if he must suddenly scan a crowded freeway for a critical road sign. This kind of model permits different processing strategies to be adopted, including sequential processing or switching. The model differs from the bottleneck models by claiming that different attention mechanisms may operate in parallel, with a lack of resources limiting the human operator's ability to perform several tasks simultaneously.

Another class of models proposes that spatial location in a visual display plays an important role in the processing of visual information. Models of attention do not generally ascribe a special role to spatial location. It has generally been assumed that selective processing is accomplished either by admitting relevant information into a particular filter or by the amount of resources allocated. However, when the human operator attends to a location in a visual display, the information at that location is processed more efficiently and at other locations less efficiently. The ability to shift attention from position to position in the visual display is now an important part of a number of attention models.

A related model suggested by Neisser (1967) is that successful processing of two stimuli or tasks depends on the extent of the operator's experience in processing those two types of input together. If operators have had considerable experience or special training in processing particular tasks simultaneously (e.g., driving a car and talking), those tasks can be accomplished simultaneously with relative ease. Learning and practice decrease the demand for the limited supply of resources, and one can drive while talking because driving, a well-practiced skill, requires little attention.

The classes of models reviewed in this section describe how the attention mechanisms are thought to function in extracting and processing information from displays. Although attention mechanisms provide the type of information that allows the human operator to perform a task, a "central processor" must coordinate ongoing serial or parallel processing activities to effectively perform a complex task. The mechanisms of selective attention will be examined and the importance of a "central processor" that performs difficult limited capacity processing will be discussed. The review will question when selective attention effects occur in processing information.

Filter Models

Broadbent (1958) suggested a single-channel model of information processing in which a peripheral filter protected a central mechanism with limited capacity from being overloaded by simultaneous stimuli. According to Broadbent, the bottleneck occurs early in the chain of internal processing. The filter selects one input and blocks out the rest, making its selection on the basis of physical cues such as spatial location, voice, intensity, and so forth. Broadbent envisioned a system in which auditory and visual inputs converge onto a switch

that can select any one incoming message, while holding messages from other inputs in a short-term store preceding the switch. Following the switch is a limited capacity channel. Once an input channel has been selected, the transmitted information has access to long-term memory and response mechanisms.

Broadbent's model, although it had considerable success, failed to account for a number of findings. The most serious objections to Broadbent's theory arose from Treisman's (1960) observations, which indicated that, under some circumstances, subjects do respond to the content of the rejected channel. Similarly, Moray (1959) has shown that when the listener's own name was inserted in the rejected message, it was recognized during approximately 30% of the trials. Subjects also identified other types of messages presented to the rejected ear, including a pure tone, a man's voice later switched to a woman's, speech and foreign language, and reversed speech. Clearly, this could not happen if rejected messages were not receiving some perceptual analysis. Results such as these led Treisman to propose that the filter merely attenuates input from rejected channels, rather than blocking it altogether.

According to Treisman (1960), information flows into the human operator through a number of parallel channels. The messages reach some part of the nervous system where they are analyzed for physical properties, such as loudness, pitch, position, color, brightness, and so forth. As well as extracting such physical characteristics, the mechanism can attenuate the signal at the output of these analyzers, and this is the way that the filter operates. Treisman's modification of the filter retained the essential idea that attended and unattended stimuli are treated differently from a very early stage of perceptual analysis.

Later, Treisman (1969) presented a more inclusive treatment of selective attention. She proposed that a single input can be processed by several different sensory analyzers in parallel, while the processing of two inputs by the same analyzer is necessarily serial. In a major departure from Broadbent's filter theory, she concluded that divided attention and parallel processing are possible for two simultaneous inputs. However, serial processing is mandatory whenever a single analyzer must operate on two inputs. Thus, Treisman's analyzer theory permits parallel processing, as when information is presented to both the auditory and visual modalities simultaneously.

In the well-known work of the physiologist, Hernández-Peón, a filter mechanism was implied in the structure and function of the nervous system. Hernández-Peón, Scherrer, and Jouvet (1956) and Hernández-Peón (1966) recorded auditory-evoked potentials from the dorsal cochlear nucleus in chronically implanted unanesthetized cats. When the cat was given some stimulus other than auditory clicks, such as visual (two mice in a closed bottle), olfactory (fish odors), or pain (shock delivered to the forepaw), the amplitude of the auditory-evoked response was attenuated markedly. These observations suggested that afferent auditory impulses were blocked at a peripheral level of the auditory pathway by some central inhibitory mechanism, which was assumed to be the mid-brain reticular formation. Hernández-Peón (1961) suggested that the reticular formation in the brain stem resembles a "high command" and that it receives all kinds of information from the external and internal environment. In turn, this region of polysensory convergence has feedback circuits that filter all the sensory impulses as they enter the central nervous system. In this way, a filtering mechanism is closely linked to the mechanisms that select which

information will be amplified at higher levels of the brain. Such a mechanism would be in concordance with the single-channel model Broadbent generated from behavioral data.

As plausible as Hernández-Peón's peripheral filtering model appears, certain methodological problems arise. The attenuation of the auditory-evoked potentials in cochlear nucleus mentioned earlier (Hernández-Peón et al., 1956) was also found to occur because of changes in the cat's position in the sound field (Marsh, Worden, & Hicks, 1962). Additional influences on auditory input have been shown to involve the middle ear muscle reflex (Baust, Berlucchi, & Moruzzi, 1964), as well as head movement (Starr, 1964). However, the physical stimulus (sound input) and the middle ear muscle reflex were controlled in subsequent experiments by Oatman (1971, 1976) and Glenn and Oatman (1977). These experiments demonstrated inhibitory effects on the auditory nerve and cochlear nucleus components of auditory-evoked potentials when animals were engaged in visual discrimination tasks.

Although Broadbent, Treisman, and Hernández-Peón retained the filter concept in their models of information processing, other authors have questioned the necessity of a filter mechanism. Deutsch and Deutsch (1963) have argued that an adequate filter requires discriminatory capacities as complex as those used in normal perception. Consequently, it has been suggested that selection occurs only after all sensory input has been completely analyzed. Therefore, Deutsch and Deutsch (1963) proposed that it was unnecessary to postulate a filter mechanism at all, since a message receives the same perceptual analysis regardless whether attention is paid to it.

Broadbent's theory asserts that it is simply impossible to divide attention among several stimuli, since attention can only be directed to one channel at a time. Deutsch and Deutsch, however, implied that it should be easy to detect an important signal, regardless whether the observer is attending to the channel on which the signal is presented. Deutsch and Deutsch (1963) imply that all stimuli reaching the senses are fully analyzed for meaning so that those of importance may receive response. However, it is difficult to understand why the rejected items, once fully analyzed, are so completely lost that no recall is possible in subsequent learning of material which has struck the ear but not received attention (Moray, 1959).

Other alternatives to filter attenuation theory have been proposed by Neisser (1967, 1969). According to Neisser's theory, selective attention is an active process of analysis by synthesis, or reconstruction of an internal representation of the input. The process transforms sensory information into a coded form which may be used by perceptual and associative mechanisms. Since the process is serial, it can process only a limited amount of input at one time. Here, irrelevant unattended messages are neither filtered out nor attenuated; they merely fail to enjoy the benefits of analysis by synthesis. Neisser indicates that he can account for the selective attention data without using a filter mechanism. His theory may adequately explain the direction of attention, but it does not adequately explain the selectiveness of attention. With simultaneous auditory and visual input, it is not clear why there is no analysis of the second input during the analysis of the first. There is an implication that this is because the analysis circuits are "busy." However, it seems that there is nothing to prevent additional inputs from impinging on the analysis mechanism, thereby disrupting the analysis of the first input. If the analysis

mechanism has a limited capacity for processing information, there is nothing to prevent other inputs from overloading it. It is apparent that although Neisser objected to the idea of a filter, the selection of messages for analysis is undistinguishable from a filtering process. Unless one postulates a mechanism that prevents the analysis of one input during the analysis of another, it appears that the rejected input should produce an information overload and cause more interference than appears to be the case. Neisser has assumed that a serial process which can accept only one input at a time is also necessarily a mechanism that prevents the analysis of one input while another is being analyzed. This assumption appears to constitute a filter mechanism.

Early Versus Late Selection

Does information selection take place early in stimulus processing, as Broadbent (1958) originally proposed, or does it take place only late in stimulus processing as Deutsch and Deutsch (1963) later proposed? As information enters the human operator from a display, it must (at least initially) be processed by a parallel, preattentive mechanism that serves to segment the display into separate objects, followed by a mechanism of focused attention that handles only one object at a time (Duncan, 1984).

Since selection must occur at some point within the processing chain, experiments were conducted to determine where in the sequence of information-processing stages the selection of information occurred. Selection could occur quite early in the chain of processing where Broadbent (1958) suggested a filter that blocked out *all incoming information* that differed from the attended information. When the parallel processing mechanism is followed by a serial processing mechanism, early selection could occur at the point when the desired information is selected and transferred to a serial processor (Hirst, 1986).

On the other hand, the bottleneck may occur late in the processing chain. The late selection view, proposed by Deutsch and Deutsch (1963) and elaborated by Norman (1968), suggested that parallel processing could occur until all the information, attended and nonattended, was fully processed. After complete processing, selection would occur based on the meaning and importance of the information. The human operator simply selected the most important information. Since the behavioral evidence has not been able to resolve this issue in favor of either early selection or late selection models, several researchers (Hillyard & Picton, 1979; Hillyard & Kutas, 1983; Oatman, 1971, 1976; Glenn & Oatman, 1977, Oatman & Anderson, 1977, 1980) have sought to determine whether brain-evoked potentials (EPs) and other event-related potentials (ERPs) can be used to index the various stages of information processing.

Rather dramatic direct evidence for the operation of an early selection model has been provided by Oatman and his co-workers (Glenn & Oatman, 1977; Oatman, 1971, 1976; Oatman & Anderson, 1977) using the brain-evoked potential. The evoked potential is the brain's electrical response to discrete environmental events, and this electrical potential can be recorded by electrodes from the human scalp or by electrodes implanted in sensory pathways in animals. The brain EPs and ERPs provide a means to evaluate the physiological events of the normal brain as it performs the various stages of information processing.

In Oatman's investigations, brain-evoked potentials were recorded from subjects while they were engaged in focused attention tasks. While the subjects were attentive to targets in a visual display, brain-evoked potentials recorded from the unattended auditory channel were significantly reduced in amplitude. Moreover, these unattended auditory-evoked potentials were suppressed in amplitude at the receptor level in the auditory pathways (see Figure 1). These results demonstrated evidence of a filter mechanism that restricts the entry of unattended information into a central processor, early in the information processing chain, so that only relevant attended inputs are fully analyzed. These findings are consistent with the Broadbent-Treisman early selection model with the idea that the filter serves to protect the central processor from possible information "overload."

Additional support for an early selection process has been provided by the research of Hillyard and his co-workers (Hansen & Hillyard, 1984; Hillyard, Hink, Schwent, & Piction, 1973; Hink & Hillyard, 1976; Schwent & Hillyard, 1975; Schwent, Hillyard, & Galambos, 1976a, 1976b; Schwent, Snyder, & Hillyard, 1976) who have observed attention-related differences between the ERP components of attended and unattended information. Hillyard has shown significant increases in evoked potential amplitude of the N1 component when subjects attended to a relevant target, compared with when their attention was directed to other (irrelevant) targets. Hillyard found that the evoked potential to targets in the attended channel is enhanced in its negative-going voltage at a very early latency--only about 100 msec after the target. This enhancement suggests that attended and nonattended targets are treated differently by the brain after only 100 msec of processing.

In subsequent studies, Hansen and Hillyard (1980, 1983) examined "difference wave forms" and observed a prolonged negative ERP (termed processing negativity or Nd wave). Since this enhanced negativity has even a shorter latency of onset (60 to 80 msec), it was also taken to be an index of an early selection process.

The electrophysiological evidence previously reviewed suggests fairly conclusive evidence that early stages of processing benefit from focused attention. The enhanced evoked potential amplitude then reflects the preferential processing of targets arriving over the attended channel, while at the same time, the inhibited evoked potential amplitude in the unattended channel reflects the gating function which allows unattended (irrelevant) stimuli to be rejected quickly and efficiently. These properties support a Broadbent-Treisman model of information processing in which a peripheral filter mechanism enhances the attended targets and inhibits nonattended targets during focused attention.

Implications for Display Design

The Broadbent-Treisman filter model postulates a limited capacity system in which sensory information is initially processed in parallel until it reaches the level of a filter mechanism. The filter serves to limit the information flow in a serial switching process, so that one input can be processed at a time, which is presumably intended to protect a limited capacity processor from excessive information load.

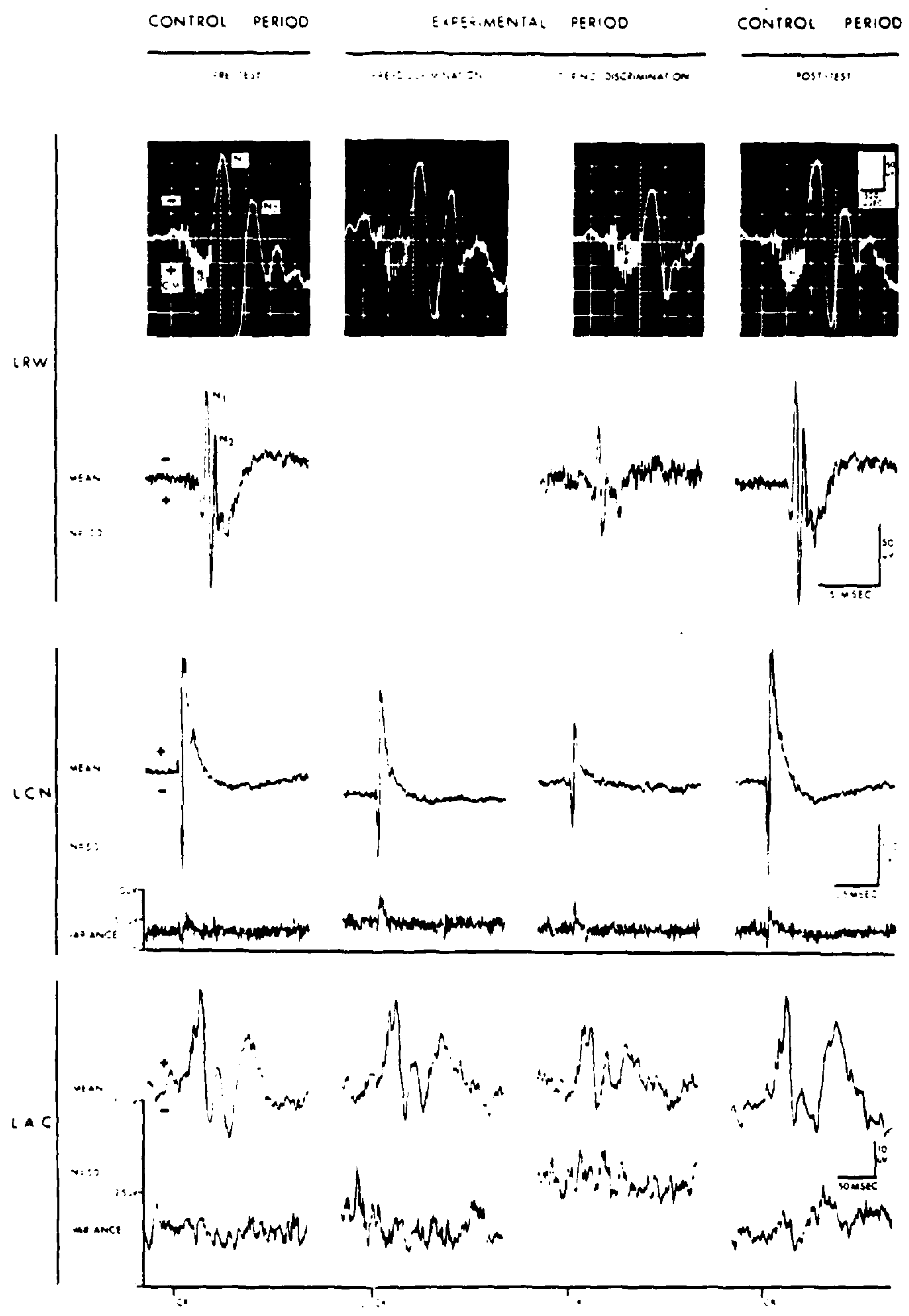


Figure 1. Averaged evoked potentials recorded from the left round window (LRW), the left cochlear nucleus (LCN) and the left auditory cortex (LAC) for different attentive states, pretest control period, experimental period, and posttest control period.

The model makes strong claims regarding information flow in the information processing system, and the implications to human factors relate primarily to display design and display formatting. Since a display serves as an interface between the human operator and a dynamic system, its structure and composition are critical to the operator's performance.

The Broadbent-Treisman model views the attention mechanism as a filter process in which target selection is based on physical features (color, pitch, loudness, etc.) of the input. Since selection is established by the filter, displays need to be formatted to emphasize the properties of these features. For example, when two sources of information occur simultaneously but only one must be attended to, performance can be improved if the attended sources of information are made distinct from one another, that is, make the attended source of information larger, brighter, louder, or more centrally located than the competing sources of information (Sanders & McCormick, 1987).

When the human operator's tasks require serial processing, the filter model suggests a display design of separate channels so that information will be processed in series. This can be achieved by enhancing the features and by using widely separated spatial locations so that unwanted information occurs outside the focus of attention.

Another implication of the Broadbent-Treisman model to display design is that performance can be improved by reducing the number of competing channels displayed or reducing the mere presence of "display clutter."

Auditory Warning Signals

Guidelines for the intensity and frequency of auditory warning signals in aircraft can be derived from the selective attention research conducted by Oatman (1976) and Oatman and Anderson (1977). Flight crews complain that the auditory warning systems are too loud (some over 100 dB), so they often turn them off.

Patterson and Milroy (1979, 1980) have noted that the levels are made as loud as possible to ensure that they will not be masked by background noise and that they will command the flight crew's attention. It has been argued that the louder a sound is, the better the chance that it will command a pilot's attention when he or she is occupied with an engrossing task such as landing the aircraft. It is presumably this kind of argument that prompted the designers to set many of the warning signals at very high sound levels.

The acoustic power of an auditory warning must be sufficient to make the warning clearly audible in the presence of the aircraft background noise, and also far enough above threshold to attract the flight crew's attention. Patterson and Milroy (1979) argued that a warning signal should be 15 dB above the threshold caused by background noise. They suggested that making the signal-to-noise ratio more than 15 dB would be annoying and needlessly aversive to normal cockpit communications. For these reasons, Patterson and Milroy suggested that warnings should be limited to about 25 dB above threshold. The appropriate range of intensities for auditory warnings would be to provide an auditory signal in the 15- to 25-dB range above the threshold.

In making the recommendation to provide an auditory warning signal in the 15- to 25-dB range above threshold, Patterson and Milroy did not adequately consider the suppression of auditory information during focused attention to a primary visual task, such as landing the aircraft or responding to an emergency situation.

Oatman's (1976) study has shown that the amount of evoked potential suppression when a subject is paying attention to a visual task depends on the intensity of the auditory warning signal. Much greater suppression occurred at low auditory signal intensities than at high auditory intensities. Figure 2 shows the amount of reduction in evoked potential amplitude as a function of signal intensity. It can be seen that during focused attention, evoked potential amplitudes to low intensity signals (45 dB) can be reduced 34 dB, whereas evoked potential amplitudes to loud warning signals (125 dB) are reduced 5 dB. In other words, the louder the warning signal, the smaller the attenuation of the auditory-evoked potentials as a function of visual attention. Based on these data, the appropriate range of intensities for auditory warning signals for aircraft would be to provide an auditory signal sufficient to override the suppression because of visual focused attention.

Oatman's findings, together with those of Patterson and Milroy, can be used to suggest guidelines for auditory warning systems. Patterson and Milroy suggested that the intensity of the auditory warning signal should be between 15 and 25 dB above threshold caused by background noise. However, the upper limit of 25 dB should be increased 20 dB (upper limit 45 dB) to override the suppression of auditory information caused by focused attention to a critical function or emergency situation. The designers of auditory warning systems will have to evaluate the trade-off between auditory signals loud enough to alert the human operator to a critical situation and auditory signals soft enough so that they do not interfere with responses required by the signal or disrupt communications when the operator is not attentive.

Patterson and Milroy (1979) also examined the frequency composition of several auditory warning systems on commercial aircraft. They described several warning signals in which the spectrum of the sound was composed of a set of harmonics with a fundamental close to 0.6 kHz and the majority of the signal energy in the region of 2 kHz. In addition, the energy was distributed across a number of audible harmonics which made the warning less susceptible to masking and contributes to their distinctive sound. Oatman and Anderson's study (1977) provides additional information about the frequency of auditory warning signals during focused attention to a visual task. This study indicated that when a subject is paying attention to a visual display, the auditory-evoked potentials are reduced in amplitude, and the amount of reduction is a function of frequency. It can be seen in Figure 3 that the amount of reduction during attentive behavior depends on the auditory frequency of the signal, in which the greatest reductions in amplitude occur at the middle frequencies (700 to 5000 Hz). These findings suggest that auditory warning signals should have most of their signal energy in the region of the spectrum where the ear is most sensitive. However, when the flight crew is attentive to a critical task or emergency situation, warning signals in those middle frequencies would require additional intensity to override the suppression caused by visual attentive behavior.

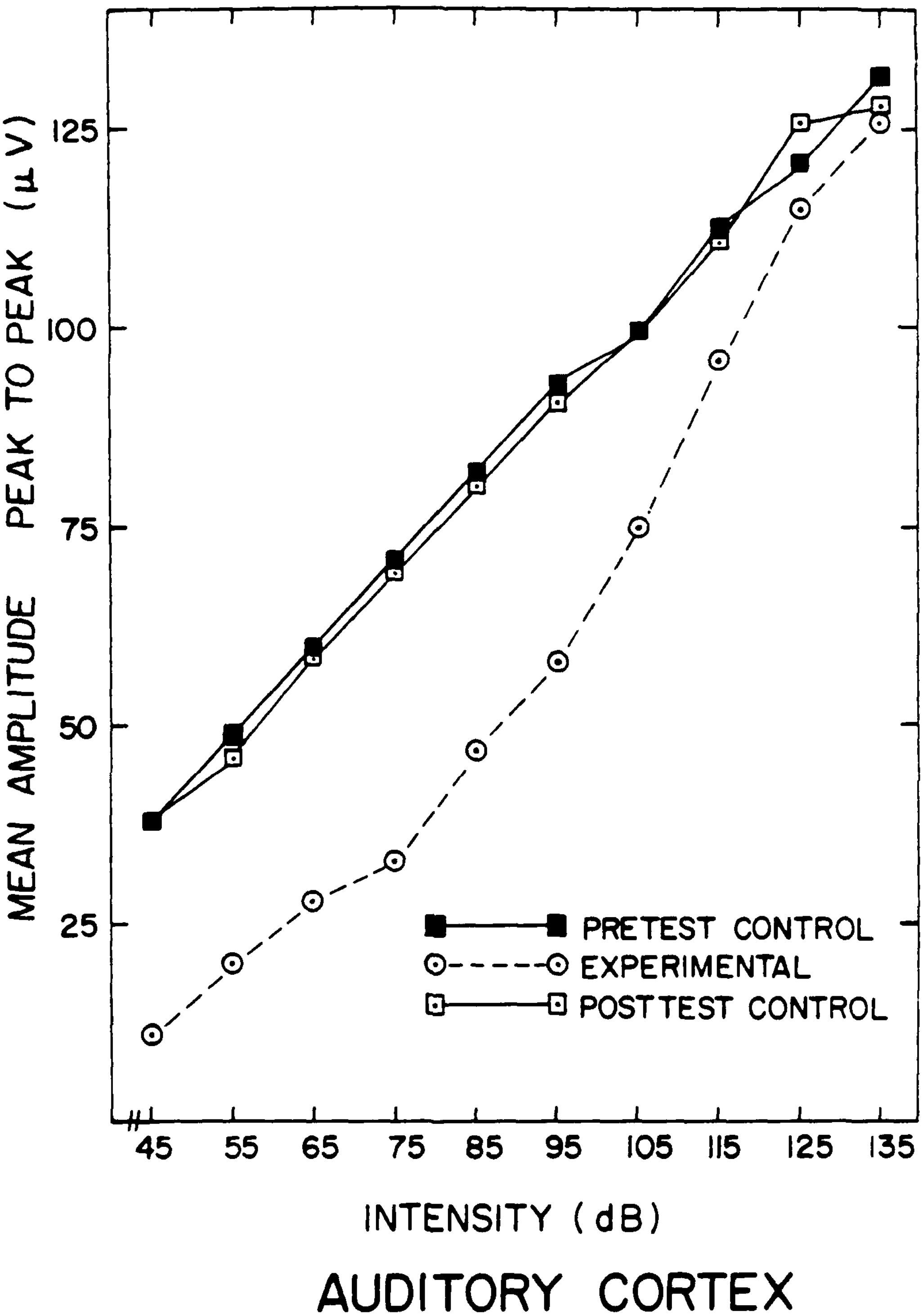
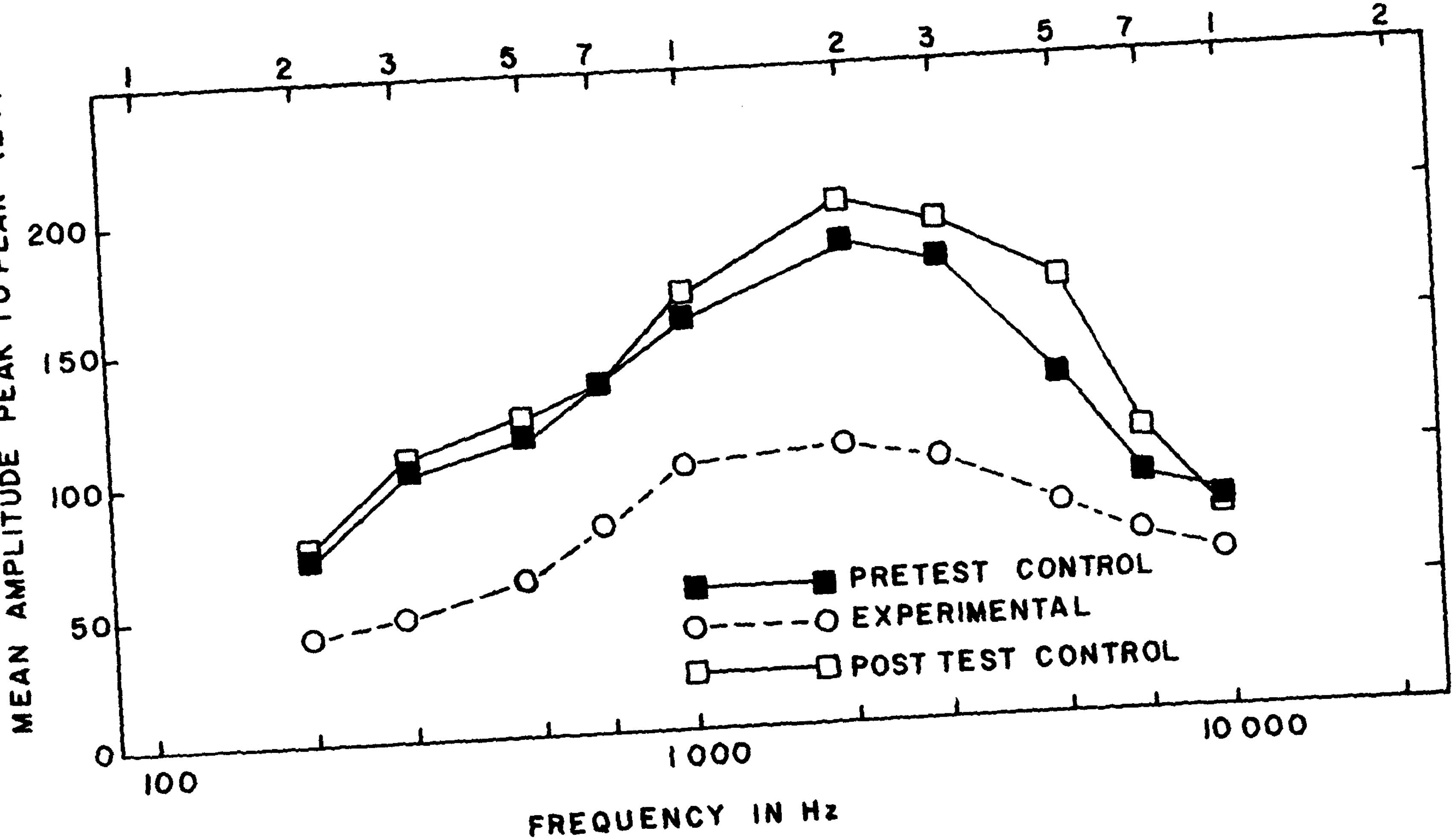


Figure 2. The average amplitude of auditory-evoked potentials recorded from the auditory cortex as a function of signal intensity and attentive (experimental) and nonattentive (pretest and posttest controls) states.



AUDITORY CORTEX

Figure 3. The average amplitude auditory-evoked potentials recorded from the auditory cortex as a function of signal frequency and attentive (experimental) and nonattentive (pretest and posttest controls) states.

In addition, with an increase in age of the flight crew, there may be significant high frequency hearing losses in some crew members. Thus, warning signals above 5000 Hz should be avoided. The warning signals should contain a number of audible harmonics which makes the signals less susceptible to masking and contributes to their distinctive sound (Patterson and Milroy, 1979).

Resource Models

Early models of selective and divided attention suggested that the human information-processing mechanism has a fixed finite capacity and that this limitation can be viewed as a bottleneck in the information-processing channel. As the bottleneck metaphor became unpopular, theorists found themselves with only the assumption of a finite capacity. Resource theory was an attempt to describe processing limitations in which attention was a limited processing capacity that could be allocated in graded amounts to various activities performed, depending on their difficulty or demand for that capacity (Wickens, 1983). Whereas Broadbent's filter model and Treisman's attenuation model treated attention as a mechanism, resource theories have no particular mechanism of attention--there is only the allocation of resources (Hirst, 1986).

Several models have been offered to explain time-sharing or divided attention performance (for a review, see Wickens, 1984). Most of the divided attention models are based on a limited pool of resources or multiple pools of limited resources that can be directed toward attention processes required to perform a task. In the following section, two major classes of such models are discussed: single-resource models and multiple-resource models.

Single-Resource Models

The concept of attention as a limited information-processing capacity initially was modeled in terms of a unitary pool of finite "mental resources." According to this view, the resources residing in the pool were undifferentiated and could be allocated with equal efficiency to any information-processing task (Kahneman, 1973). The primary assumption was that the processing resources for any system are limited and that mental processes must therefore compete for supplies from the same common pool. Implicit here is the idea that information processing may occur in parallel without observed performance decrements, so long as the total capacity available has not been depleted. As task demands increase either by making a given task more difficult or by imposing additional tasks, more of these attention resources are required. As the total capacity available is exceeded with increased task demands, performance deteriorates. Thus, interference between tasks performed concurrently implies that they draw resources from a common pool. This model explains very nicely why performance in a dual-task situation declines as the difficulty of one of the tasks increases. The increase in task difficulty demands more resources from the limited supply, thus leaving fewer resources available for performing the other task (Sanders & McCormick, 1987).

According to this model, the human attention mechanism is assumed to possess some limited resources that can be allocated to different tasks or classes of stimuli (Navon & Gopher 1979). The amount of resources that a particular attention mechanism requires to process displayed information has been

determined by examining the effects of focused attention on competing displayed information in an auditory-visual interaction situation. The extent of such interaction can be predicted by considering the demands that competing input channels impose on a common pool of resources.

Oatman (1971, 1976, 1982) and Oatman and Anderson (1977, 1980) examined the attentional demands on a common "pool" of resources when processing auditory and visual information simultaneously. Allocations of attention among competing visual and auditory information were reflected in the evoked potential amplitudes. Oatman (1971) demonstrated that as attention increased to the visual display, the auditory-evoked potentials gradually decreased in amplitude (see Figure 4), suggesting that these evoked potentials were indexing the allocation of processing resources from a limited pool. As the subjects were more attentive to the visual display, a greater amount of resources were allocated to the visual display, thus leaving a lesser amount of residual resources available for monitoring the auditory information.

Glenn and Oatman (1977) further explored this phenomenon by using latency measures as well as measures of amplitude. In this study, when the subjects were attending to a visual display, the evoked potential amplitudes to auditory signals were reduced and the latencies of those evoked potentials were increased. The magnitude of these changes was influenced by the degree of attention required, suggesting that attention can consume processing resources and that the amount consumed increased as the amount of information was increased (Johnston & Heinz, 1978).

When the subjects were paying attention to the visual display, not only were the auditory-evoked potentials suppressed in amplitude, but significant increases in hippocampal RSA (rhythmic slow activity) were also observed (Oatman, 1982). Oatman observed that the amount of power within the theta frequency range (4 to 8 Hz) was significantly larger during attention to a visual display than during nonattention (see Figure 5). Oatman suggested that during attention to visual stimulation, the function of the hippocampus is one of gating or filtering, which allows a subject to ignore or filter out background, irrelevant stimuli (Moore, 1979; Solomon, 1979, 1980; Solomon & Moore, 1975).

Perhaps the observed suppression of auditory-evoked potentials and the increased amount of hippocampal theta were actually the result of increased sensory stimulation rather than the result of attentional mechanisms. To examine this possibility (Oatman, 1986), the same experimental paradigm was used that was used in the attention studies, but no attempt was made to alter the attentive state of the subjects. The results showed no significant change in the amount of power within the theta frequency range with increased light intensity, except at the most intense level (323 lux) of stimulation. On the basis of these results, it seems unlikely that suppression of auditory-evoked potentials and the increased hippocampal RSA demonstrated in previous attention studies were the result of increased sensory stimulation or sensory interaction. These studies also suggest that as a primary visual task demands more attentional resources, less attentional resources are available for processing secondary (auditory) information.

Allocations of attentional resources have also been assessed through changes in P300 amplitude elicited by competing auditory and visual tasks. Isreal, Chesney, Wickens, and Donchin (1980a, 1980b) recorded the P300 in a

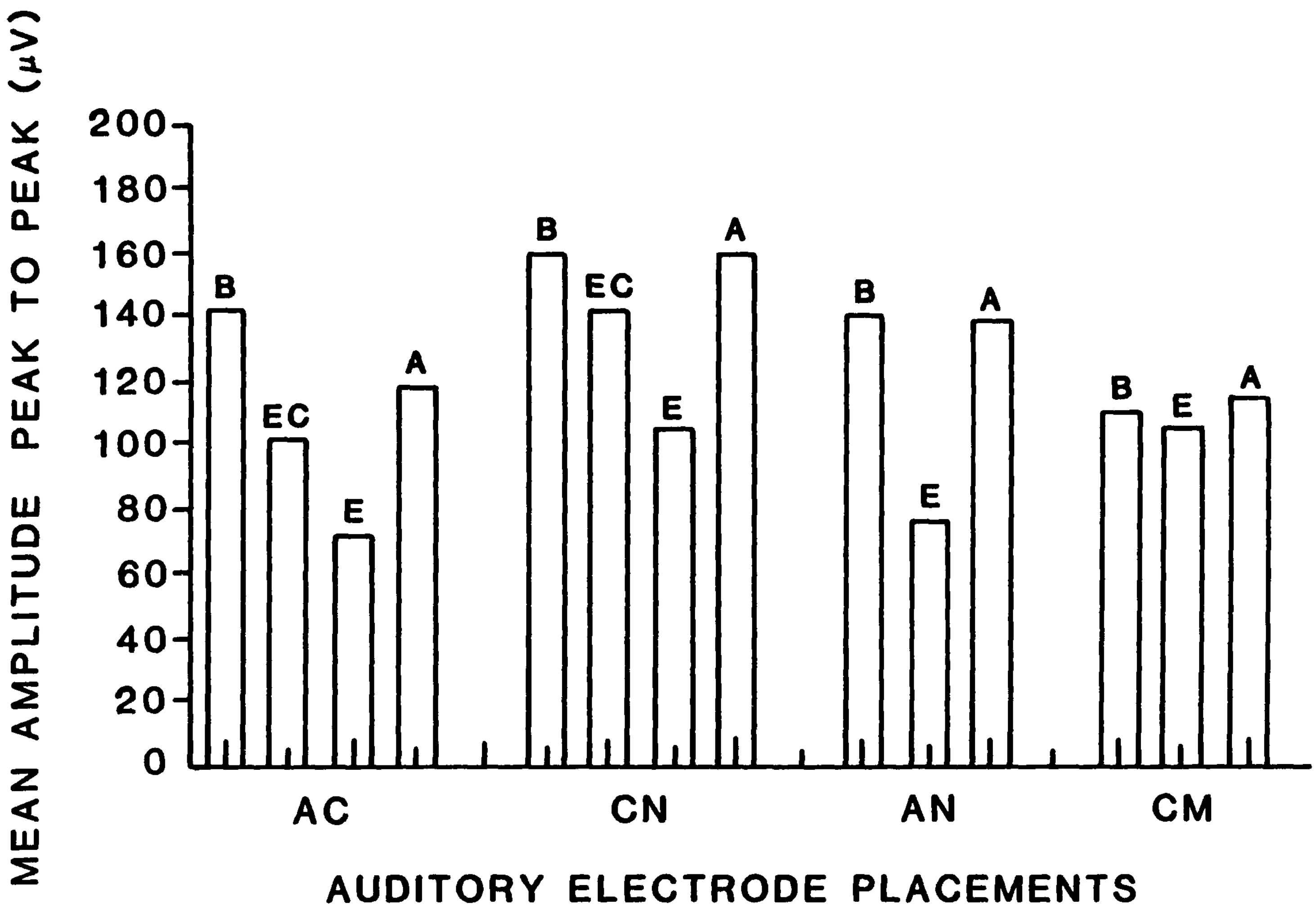


Figure 4. Averaged auditory-evoked potentials recorded from the auditory cortex (AC), cochlear nucleus (CN), round window (auditory nerve [AN] and cochlear microphonics [CM]) for different attentive states, control before (B), experimental control (EC), experimental (E), and control after (A).

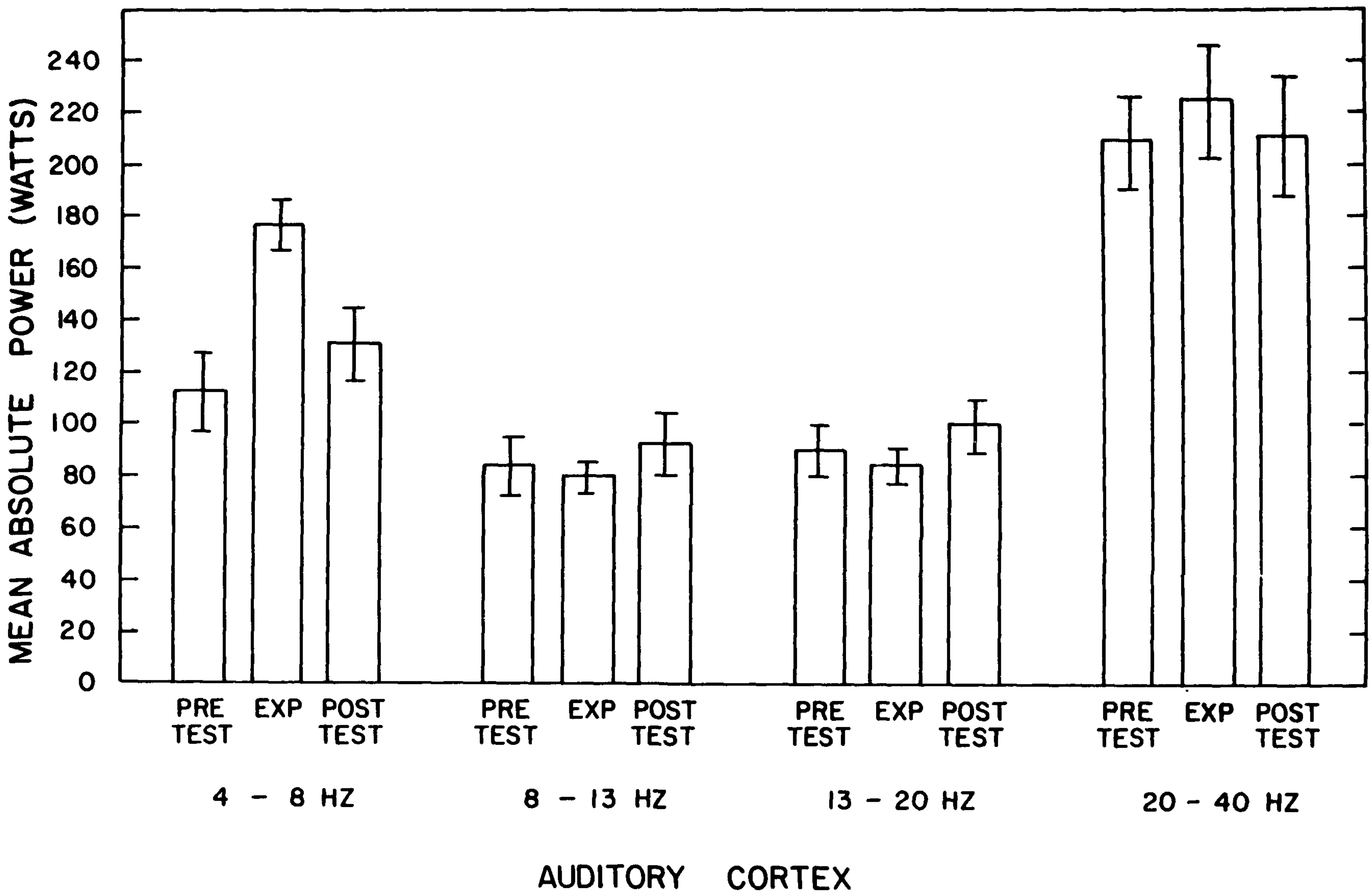


Figure 5. The average absolute power (pWatts) computed for four frequency bands as a function of attentive (experimental) and nonattentive (pretest and posttest) states.

secondary tone detection task performed simultaneously with a primary visual tracking task. These authors found that P300 amplitudes from the secondary auditory task were decreased when the perceptual demands of the primary visual tracking task were increased, but not when the response demands became more difficult. These results suggest that P300 indexes the processing resources involved with two competing tasks. However, since reaction time data failed to differentiate increases in perceptual load from response load, the P300 measures were also critical in demonstrating that resources can be drawn from functionally different independent resource pools.

Sanders and McCormick (1987) have suggested that the problem with the single-resource theory is the difficulty in explaining why in some dual task situations, the increasing difficulty of one task has no effect on the performance of the other task, and why some tasks can be time-shared without a decrement in performance of either task (Wickens, 1984). The notion of a single, central resource pool has been challenged by the idea that multiple, independent resource pools may exist (Navon & Gopher, 1979; Wickens, 1980).

Multiple-Resource Models

The multiple-resource view postulates that there is not a single pool of undifferentiated resources; rather, resources may be of a number of different types, each with its own limited capacity. In this view, the existence of multiple types of resources allows complete, partial, or no overlap in the particular resources demanded by any two tasks. The extent to which two tasks can be successfully time-shared depends on the degree to which they overlap in demanding resources of a particular type. Only when tasks share the same resource pools will performance be disrupted, whereas tasks that draw from different resource pools might be performed concurrently without interference. The implication is that the greater the overlap in resource demand, the larger the amount of mutual interference that could be observed in a dual task situation. Conversely, the smaller the overlap in the resource compositions of two tasks, the smaller the amount of trade-off in performance observed.

Wickens (1980, 1984) has expanded the multiple-resource theory by trying to articulate the exact nature of these resource pools. Wickens, drawing upon the results from a large number of dual task studies, has suggested that resource pools may vary on three relatively simple dimensions: stages of processing (perceptual-central versus response processes), codes of processing (spatial versus verbal), and modality of input (auditory versus visual encoding).

Implications for Display Design

The multiple-resource model (Navon & Gopher, 1979; Wickens, 1980) of information processing may provide useful guidelines for the design of human-system interfaces. This class of models differs from the earlier ones in that multiple-resource models predict no interference between two concurrent tasks under specific design situations (Whitaker, 1984). Whereas earlier models assumed that tasks were handled through the use of a single limited capacity attentional reservoir, the newer model assumes multiple processing resources. Each resource is basically committed to some specific process, which allows two tasks to be performed concurrently without interference, provided they both use

different resource pools. Wickens has suggested that the human operator can draw from a number of separate attentional resources to perform a complex task (e.g., fly an aircraft). If his model is correct, displays can be designed to make optimal use of these separate reservoirs of resources within the operator.

Friedman, Polson, DaFoe, and Gaskill (1982) suggested that the types of resources demanded by a particular attentional mechanism may overlap with those demanded by others either completely, partially, or not at all. This has implications for the kinds of interaction effects and trade-offs to expect when competing information is displayed simultaneously. If two competing messages draw resources from the same modality, and if they each can be processed using only that particular resource, their resource demands completely overlap. As these required resources become scarce, there would be an overall decrement in performance, as in the case of sensory overload. For example, listening to auditory warning signals will be disrupted by the simultaneous requirement to understand a conversation which also demands the auditory channel. The multiple resource model suggests a design criterion that seeks to minimize the overlap of attentional demands on common resources.

A major goal of display research (Wickens, 1984) is to enable the system designer to predict what effect a particular design innovation (i.e., a change in a parameter of a primary display) will have on the sensory processing experienced by the operator. The innovation may increase the demand for attentional resources. Such a design change can lead to the operator's attentional resources being exceeded, and thus lead to a decrement in performance. However, the designer may restructure the design of the primary display or alter the temporal presentation of the information on the display, so that the operator's attentional resources are sufficient to handle sensory processing demands.

Spatial Attention Models

The role of stimulus location in the selective processing of visual information has attracted much interest in recent years (e.g., Duncan, 1981, 1984; Eriksen & Hoffman, 1973; Hoffman & Nelson, 1981; Kahneman & Henik, 1977, 1981; Nissen, 1985; Posner, Snyder, & Davidson, 1980; Treisman & Gelade, 1980; Tsal & Lavie, 1988). Some researchers believe that spatial location plays a unique role in the selection of information for further processing (e.g., Posner et al., 1980), whereas others claim that it is just one selection dimension (although an extremely efficient one) that is not different in principle from other stimulus dimensions, such as color or shape (e.g., Duncan, 1981).

The ability to shift attention to different areas of the visual display is a very important component of a number of models. Posner's (1980) scan mechanism allows a shift of attention spatially from one part of the visual display to another. Similarly, models of the visual system (Treisman & Gelade, 1980) postulate an ability to bring attention to any location. The evidence shows that when the human operator attends to a location in the visual display, information at that location is processed more efficiently than at other locations.

Automatic and Controlled Processing

One of the most remarkable findings in processing information from visual displays is the human operator's ability to separate automatic unattended processing of information from attended, active processing of information (Posner, 1978; Shiffrin & Schneider, 1977). The distinction appears to be a fundamental one and one that may illuminate problems of information processing from visual displays.

Schneider and Shiffrin (1977) have developed a two-process theory of human information processing, based in large part on the effects of practice in scanning visual displays. Human performance in processing information from visual displays is the result of two qualitatively different processing modes referred to as automatic and control processing. In scanning visual displays, automatic information processes are fast, parallel, inflexible, do not require attention or compete with other processes for capacity, and are responsible for the performance of well-developed skilled behaviors. Automatic processes develop with consistent practice, and (once initiated) are not under the human operator's direct control. Attended or control processes are slow, serial, flexible, require attention and capacity, and play a critical role in processing novel or inconsistent information. Control processes are under the human operator's direct control, and are expected when the human operator's response to the target varies from trial to trial.

The importance of the distinction between control and automatic processing warrants some additional elaboration. In a visual search task, Schneider and Shiffrin (1977) explored the role of training in automatic and controlled processing. In the search paradigm, subjects are required to determine whether any one of a set of targets is present in a visual display. In one training schedule called consistent mapping (CM), the targets and nontargets are always drawn from two different sets of stimuli. Extensive training can gradually reduce the slope of the function relating search reaction time (RT) and processing load to some 10 msec or less (Hoffman, Nelson, & Houck, 1983). In another training schedule called variable mapping (VM), the targets and nontargets are drawn from the same pool of stimuli such that targets and nontargets periodically exchange roles. Thus, a stimulus that is a target on one trial can be a nontarget on another trial. VM training results in controlled search where the slope of the function relating RT and processing load for target-absent trials is usually twice that for target-present trials (Hoffman, Nelson, & Houck, 1983).

Schneider and Shiffrin suggest that CM search corresponds to automatic processing that is rapid, parallel, and makes few demands on attention, whereas VM search corresponds to control processing that is slow, serial, and attention-demanding. In searching visual displays, Schneider and Shiffrin (1977) propose a fundamental transition between the two modes of information processing. When the target is changed on every trial, the attentional demands require a controlled search process, but when the same set of stimuli are consistently assigned to the target set for many trials there is a gradual shift from controlled to automatic search.

One important implication of the automatic or control processing model is that automatic processes do not require attention (Hoffman, Nelson, & Houck, 1983). However, there have been several reports indicating that automatic

processes are affected by attention. Attention has been found to be important in semantic priming (Hoffman & MacMillan, 1985; Johnston & Dark, 1982) and detection of familiar targets (Hoffman, Nelson, & Houck, 1983).

Hoffman, Simons, and Houck (1983) examined whether automatic detection requires attention using the P300 component of the human event-related brain potential. They demonstrated that both automatic and nonautomatic search tasks produced P300 components of comparable amplitude, which suggests that both tasks made similar demands on attention. However, P300 latency was significantly shorter when subjects engaged in automatic search. These results suggest that the latency of the P300 was reduced by training on the automatic detection task, which produced fast and efficient processing, but still depended on a limited capacity system (Hoffman, 1986).

In another study, Hoffman, Houck, MacMillan, Simons, and Oatman (1985) examined the role of attention in the detection of automatic targets in a dual task paradigm using both behavioral and event-related brain potentials (ERP) measures. An automatic detection task was paired with another concurrent visual discrimination task, while the amount of attention allocated to each task was systematically varied. Subjects were required to make a detection response for each task on every trial.

The behavioral data showed that both the speed and accuracy of responses to automatic targets decline when subjects are required to combine the two tasks. The P300 amplitude for each task was a function of the relative amount of attention allocated to that task. The P300 amplitude for the two tasks traded off in a linear fashion that closely mirrored the trade-off in performance under the same conditions. In other words, withdrawal of attention from the automatic task resulted in a decrease in accuracy that is reflected in the P300 amplitude. The same linear relationship between detection accuracy and P300 amplitude was observed for both tasks, which suggests the presence of a single attentional resource required by both tasks.

In contrast, there was a dissociation between response latency and P300 latency on the automatic detection task. Response latency increased continuously as attention was withdrawn from the automatic detection task and allocated to the comparison task. However, P300 latency increased by an amount that was an order of magnitude smaller. In addition, whereas response latency increased continuously with reductions in attention to the automatic detection task, P300 latency increased by a constant amount regardless of the specific allocation of attention between tasks. The dissociation between P300 latency and response latency provides evidence for a separate limited capacity process concerned with motor responses.

The automatic or control processing model has provided an interpretation of the human operator's performance in searching visual displays. According to this model, performance in searching visual displays is determined by processing mode, automatic and control or attended processing, and the transition between the two modes is a function of training. Several experiments have demonstrated that subjects can perform two tasks concurrently without significant deficit if one of the tasks can be performed via automatic processing (Fisk & Schneider, 1983, 1984; Schneider & Fisk, 1982). This line of research has shown that when performance deficits occur as a result of increased competition for attentional resources, the deficits result from an inability to

concurrently perform attended or control processing tasks. However, Hoffman et al., (1983, 1985) have shown that while training on the automatic detection task produces fast and efficient processing, the automatic processing mode may still depend on a limited capacity system of attentional resources.

Attentional Spotlight

Attentional spotlight theories (Eriksen & Hoffman, 1973; Hoffman & Nelson, 1981; Posner et al., 1980) propose that at any given moment, attention is focused on a particular area of a visual display, and only stimuli within this area receive full perceptual analysis. The limit on the human operator's ability to see several things at once is seen as a limit on the spatial area from which information can be picked up.

An accumulated body of evidence suggests that attention operates as a spotlight that illuminates an area within which stimuli are processed in detail (e.g., Eriksen & Hoffman, 1974; Posner et al., 1980), and outside this area facilitation gradually declines with greater distance from the attended location (Downing & Pinker, 1985). The spotlight appears to have a central focus (Posner et al., 1980), and may flexibly adjust the size of its beam to fit the demands of the visual task (Humphreys, 1981). The beam can assume a small area of about 1° (Eriksen & Hoffman, 1973), or as with a zoom lens, it can be made larger at the cost of a loss in definition (Treisman & Schmidt, 1982).

Although Posner, Snyder, and Davidson (1980) have shown that the attentional spotlight is not related to the area of clear foveal vision, there is a strong belief that attention is tied closely to the fovea. This strong assumption is usually appropriate, since we are always moving our eyes to objects that interest us, and thus we are habitually paying attention to those objects. However, their results have shown that when the fovea is not in the attentional beam, its ability to lead to detection is diminished, similar to any other area of the visual system.

The activation of the attentional spotlight is apparently controlled by locations within the visual display, such that, for example, even the processing of unrelated stimuli within the illuminated area would be facilitated (e.g., Eriksen & Hoffman, 1973; Hoffman & Nelson, 1981). The attentional spotlight can automatically be attracted to the location of a peripheral cue in a visual display (e.g., Jonides, 1981). It can be directed by a central cue pointing to a given location in a visual display (e.g., Posner et al., 1980), or be directed to the location of a target that was initially selected on the basis of a different property (e.g., a red target in a multicolor display calls attention to its location [Tsal & Lavie, 1988]).

Strong support for the spotlight theory was provided by Hoffman and his associates (Hoffman & Nelson, 1981; Hoffman, Nelson, & Houck, 1983). Their subjects searched displays of four letters for predetermined targets. At the same time, a small box with one side missing was presented near one of the letters, and for this task, subjects had to locate the missing side. Performance of the search task was more accurate when the box was adjacent to the target than when it was not, a result replicated and extended by Hoffman, Nelson, and Houck (1983). Hoffman and Nelson (1981) suggested that the box attracted the attentional spotlight to its vicinity, improving the detection of adjacent

targets. However, Duncan (1984) suggested that this finding reflects the strength of perceptual grouping rather than adjacency per se. Since identifying several targets in a complex display is best when they form a strong perceptual group, Duncan argued that in the Hoffman and Nelson (1981) displays, the box and the letter target would have formed the strongest group when they were adjacent, and the strength of perceptual grouping, rather than adjacency per se, determined performance in these experiments.

Additional support for the idea that attention operates as a spotlight was provided by Prinzmetal, Presti, and Posner (1986) who found that directing attention to stimulus location before stimulus onset enhances the perception of its features. Tsal and Lavie (1988) suggested that the operation of the attentional spotlight mechanism is strictly controlled by the location within a display in such a way that relevant and irrelevant information are kept separate in the course of visual selective processing. They demonstrated that attention is allocated to the vicinity of a relevant target even when it is cued by color or by shape rather than by location. Thus, according to Tsal and Lavie (1988), enhanced selective processing of targets defined by color or by shape is accomplished by increasing the sensitivity of the location that these targets occupy in the visual display, rather than by the operation of internal structures representing these selection attributes.

Orienting Spatial Attention

How is the attentional system brought to bear on a visual display? The model proposed by Posner (1980; Posner, Cohen, & Rafal, 1982; Posner & Cohen, 1984) addresses this question. Posner's model distinguishes between two different aspects of the attentional system. The first is orienting or aligning a central attentional system with a visual display, and the second is detecting targets within the visual display.

Orienting involves the direction in which attention is pointed, and can be viewed as the selection of a location within the visual display. However, orienting may also involve the selection of a modality, and within modalities, it may differ based on the nature of the organization of information in that sensory system (Posner, 1978). When input involves more that one modality, it is possible to compare orienting by modality with orienting by position in the visual display. When this is done, modality information dominates over spatial position.

Orienting also includes detecting. By detection, Posner means the contact between the attentional system and the target signal, such that the human operator can make an arbitrary response to it. In the real world, it is usual for a target to produce both orienting and detection. Experiments (Posner, Snyder, & Davidson, 1980) have clearly shown that the human operator's knowledge about where a target will occur in the visual display affects the efficiency of detection. Thus, when attention is directed to a particular spatial location in a visual display, targets that have this location are processed more efficiently (faster responses, lowered thresholds) than if attention is not so directed. Targets that do not have the particular spatial location are handled more poorly than otherwise.

The model proposed by Posner (1980; Posner, Cohen, & Rafal, 1982; Posner & Cohen, 1984) assumes that the orienting of spatial attention includes both overt and covert operations, directed by specific neural systems. When a signal in the visual display alerts the human operator, the head and eyes move toward the signal--an overt alignment of attention. However, attention may also be directed toward the signal without any head or eye movements--a covert alignment of attention (Posner, 1980). Everyone has had the experience of having their attention drawn by something in the periphery of their visual field before making an eye or head movement to fix the location of interest. The covert shift of visual attention can also be divided into more specific mental operations of disengaging from the current focus of attention, moving attention to the cued location and engaging the target (Posner & Presti, 1987).

Attention may be summoned to a particular spatial location by the presentation of a visual cue (Posner, 1978). The cue may appear in the location to be selected or may consist of an arrow presented at fixation (in the center of the visual display) that points toward the location to be selected. After a variable time interval, a target is presented, usually in the same location as indicated by the cue and occasionally in a different location. Cognitive studies have shown that cuing attention to a visual location without movement of the eyes improves the efficiency of detecting targets as measured by reaction time (Posner, 1980), reduced threshold (Bashinski & Bachrach, 1980) and increased electrical activity from the cued location (Mangun, Hansen & Hillyard, 1986).

Although both central or peripheral cues will produce facilitation or improvements in the efficiency of detecting targets that occur at the cued location in comparison with uncued locations, inhibition arises when the attention mechanism has been summoned by a peripheral cue to a position away from the fixation point. Inhibition is demonstrated most clearly if attention is then summoned back to fixation. The previously facilitated location is now inhibited in comparison to other locations (Posner & Cohen, 1984). The inhibition effect serves to bias the next few attentional shifts toward the gathering of information from new locations. Such an inhibition effect may serve to maximize sampling of the visual display (Posner & Presti, 1987).

Feature Integration Model

The feature integration theory of visual attention (Treisman, 1982; Treisman & Gelade, 1980; Treisman & Souther, 1985; Treisman & Gormican, 1988; Treisman, Sykes, & Gelade, 1977) describes the role of attention in the perception of objects that has implications for how the human operator processes information from visual displays. The theory distinguishes between two processes: (a) feature detection, the initial, preattentive process, and (b) feature integration, which requires attention.

In the first process, a visual display is initially encoded as a set of features along a number of separable dimensions. In this context, dimension refers to the complete range of variation (such as color, orientation, or shape), whereas feature refers to a particular value on one of these dimensions (red, vertical, or square). The initial, preattentive process permits the detection of features and underlies segregation of targets by textural cues, but contains no information about the way the features combine or about their locations within the visual display. According to Treisman's theory, the latter functions operate

accurately only when the visual attention mechanism is focused on individual locations, one at a time, integrating the different features present at those locations. Feature detection is automatic, spatially parallel, and free of capacity limitations.

In the second process, feature integration, focused attention is required to integrate the separable features into unitary objects. Objects in the visual display are synthesized by focusing attention on one location and combining the separable features (e.g., size, color, shape, texture, orientation) occurring at that location. Once the compound objects have been correctly registered, these continue to be processed and stored as such. Thus, focused attention provides the "glue" which integrates the initially separable features into unitary objects. Without focused attention, features cannot be correctly related to each other. If attention is overloaded or diverted from a display, the features from different objects in that display may be wrongly recombined, forming "illusory conjunctions" (Treisman & Schmidt, 1982). An illusory conjunction is the incorrect joining of two or more features from separate items in a display to create a new, unpresented object. Illusory objects may recombine either dimensions, like shape, size, and color of different real objects, or component parts, like the curves, lines and angles of more complex shapes.

Thus, feature detection suffices to discriminate items containing different features. Treisman and Gelade (1980) showed that visual search for targets defined by one or more disjunctive features (e.g., blue or curved) occurs in parallel and preattentive across a visual display. The implication of this model is that target detection may precede correct location of the target, particularly when single-feature target recognition is possible. However, feature integration is required for discriminating items that contain differing combinations of the same features. Visual search for a conjunction target (e.g., red and vertical) requires a serial, self-terminating scan through items in the display, suggesting that attention must be focused on each item in turn (Treisman & Gelade, 1980). Thus, one important role of focused attention and serial processing is to integrate separable features into the correct conjunctions, which correspond to the objects actually presented. The implication of this model is that when a visual search task requires accurate conjunction of different features (e.g., color and form), the human operator must attend to the display elements one at a time.

In a different elaboration of the space-based view, the following authors suggested that visual attention acts to take up all information from a particular area of space but that the shape of this area can be determined by a prior stage of Gestalt grouping and segmentation of the visual field, very much as envisioned by the object-based theory: Treisman (1982); Treisman & Gelade, (1980); Treisman & Schmidt, (1982); Treisman & Paterson, (1984). For example, it may well be possible for such a mental spotlight to assume the shape of either the box's contour or the line, in the present displays; and this may be expected if grouping cues indicate that the box and the line are separate objects. The chunk of information dealt with by focal attention is determined by Gestalt grouping, not by anything specifically spatial. A further point is missed by such a conclusion, however. Treisman proposed that the function of focal attention is to link together information concerning an object's different attributes. Preattentively, separate "maps" of the visual field are formed for different stimulus attributes: color, size, aspects of shape, and so forth. Within each map, Gestalt grouping factors can operate to indicate candidate areas

for focal attention. Focal attention then acts on a particular candidate area and links together into a single perceived object the information from this area in all the separate maps.

Implications for Display Design

The spatial models propose that perceptual analysis of the visual display takes place in two successive stages. Stage one requires a preattentive, parallel mechanism which rapidly and readily extracts features such as color or movement within the entire visual display. Simultaneous processing in parallel without interference is characterized as fast, inflexible, and attention-free and is said to be automatic.

Stage 2 requires focused attention for a detailed analysis of the content of limited areas of the visual display. Focused attention is serial and characterized as slow, flexible, and demanding in attentional resources.

For systems design, the automatic or control model demonstrates that the human operator can perform two tasks concurrently without significant deficit in performance if one of the tasks can be performed by Stage 1, automatic processing.

The attentional spotlight model suggests that the spotlight can be automatically attracted to the target in a visual display. For systems design, this indicates that targets should be enhanced by a different property (e.g., a red target in a multicolor display) to activate the attentional spotlight. When the human operator must distinguish relevant and irrelevant targets in a display, any increase in the difference between the two is likely to be helpful. In addition, nontargets should be positioned away from the target in the display to avoid the attentional spotlight. The farther from the target irrelevant stimuli are placed, the less likely they are to fall within the spotlight and thus to be processed.

The orienting attentional model suggests that attention may be summoned to a spatial location within the visual display by the presentation of a visual cue. The evidence demonstrates that cuing attention to a visual location improves target detection performance and shortens search times.

The implication of the feature integration model is that when a visual search task requires accurate conjunction of different features (e.g., color and form), the human operator must attend to the display elements one at a time. If the visual display is designed so that a potential target has only one separable feature, the assumption of automatic processing is very plausible. However, if it is accepted that for positive trials a conjunction of two or more separable features of a target must be made before detection can occur, feature integration processes would be required.

CONCLUSIONS

One of the major areas of human factors research has been in the design of displays for military electronic systems. A display serves as an interface between the human operator and a dynamic system, and its structure and

composition are critical to the operator's performance. Research directed toward design criteria for displays has primarily dealt with the information itself and techniques for formatting, coding, and organizing the displayed information. However, neither of these areas of research has adequately considered the capabilities and limitations of the human operator.

A principal goal in human factors engineering is to design a visual display format that will match the attentional mechanisms of the human operator. A display compatible with the human operator's attention mechanisms will improve performance by allowing faster, more accurate information processing, and will minimize mental work load. To accomplish this goal, the system designer must develop a conceptual model of the system that is appropriate for the user, and also must develop a conceptual model of the functioning of the attention mechanism to extract information from the display interface.

Attention models will serve the system designers well if they are able to predict the human operator's performance that will be activated by different possible interface configurations and display formats (Rasmussen 1986). This report has reviewed several different classes of attention models, such as filter models, resource models, and spatial models, which are descriptions of the functioning of the human operator's attention mechanisms in extracting information from visual displays during the performance of different types of tasks. It is important to provide system designers with several theories and models of human attention mechanisms since the designer's effectiveness in applying human factors principles continues to depend largely on his or her own experience and intuition (Meister, 1984; Kantowitz, 1985).

However, the way in which the human operator responds to a display depends on how the operator understands that display (Rouse & Rouse, 1979). Further, it depends on the human's abilities to attend to display stimuli to produce the desired task performance. Therefore, we have to know a great deal about the human operator's attention mechanisms as well as the display format to be able to design human-system interfaces successfully.

This basic research program at HEL has focused on the attention mechanism of the human operator per se--how do attention mechanisms function to extract and process information? Research summarized in this report was conducted to examine the capabilities and limitations of the human operator's attention mechanisms in the processing of information from visual displays.

The following points need to be emphasized:

1. Clear evidence has been presented that human operators have basically different internal modes of information processing, which are put into operation by different types of performance tasks. A distinction between two levels of visual information processing is beginning to emerge. One aspect of visual processing seems to be accomplished simultaneously (i.e., for the entire visual field at once) and automatically (i.e., without attention being focused on any one part of the visual field). Another aspect of visual processing seems to depend on focused attention and is done serially, or one at a time, as if a mental spotlight were being moved from one location to another.

2. Rather dramatic direct evidence for the operation of an early selection filter model of attention has been provided using the brain-evoked potentials.

a. When a subject is attentive to targets in a visual display, the amplitudes of unimportant auditory-evoked brain potentials are suppressed; much greater suppression occurs at low auditory intensities than at high auditory intensities; greater suppression occurs at the middle frequencies (700 to 5000 Hz) than at higher or lower frequencies; significantly increased amounts of 4 to 8 Hz (theta) brain activity were present.

b. When a subject is not attentive to a visual display, high intensity light had no effect on auditory-evoked potential amplitudes; no significant amounts of 4 to 8 Hz (theta) brain activity were present.

c. When a subject is attentive to an auditory display, the amplitudes of unimportant auditory-evoked brain potentials are not suppressed; no significant suppression occurs at low auditory intensities or at high auditory intensities; significantly increased amounts of 4 to 8 Hz (theta) brain activity were present.

3. The focusing of attention is very effective in attenuating irrelevant stimuli and keeping irrelevant stimuli from interfering with primary display information. The selective process depends on the ease with which relevant stimuli can be segregated at the periphery and the effectiveness of rejecting irrelevant stimuli depends on the amount of capacity the primary display demands.

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